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NUMERICAL MODELLING OF THE CYCLIC BEHAVIOUR OF TIMBER-FRAMED STRUCTURES USING *OPENSEES*

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Abstract. *Timber frame structures constitute an important cultural heritage of many countries, since they represent a typical anti-seismic construction adopted worldwide and are worth preserving. While these structures have recently been studied experimentally to better understand their behaviour during seismic actions, little studies have been carried out on the numerical modelling of such structures, which could help in improving interventions and retrofitting measures in existing buildings.*

This paper presents a study on the applicability of numerical models in predicting the global response of timber-framed shear walls during earthquake events. Based on the in-plane cyclic testing of traditional timber frames with and without masonry infill performed in a previous experimental campaign, numerical models were developed that capture the cyclic response of traditional timber frame walls including flexural behaviour, pinching and strength degradation. The numerical models were constructed in the finite element software OpenSees with calibrated springs representing nailed connectors found in traditional half lap joints and based on experimental results.

A parametric study was conducted on the half-timbered frame model by varying wall configuration and studying cumulative energy dissipation and the effect of slenderness and load capacity with increasing drift.
All models developed showed a very good approximation of the experimental results, in terms of initial stiffness, maximum load and energy dissipation. Future work includes the development of a macro-model and modelling of a whole timber-framed building in order to improve modelling capacities and predictions.

1 INTRODUCTION

Ancient heritage is abundant with timber-framed structures that function as strengthening solutions with infill and as independent structural systems. In earthquake areas they have been used as seismic-resistant construction and their good behaviour during seismic events has been documented and observed in a number of countries (e.g. Portugal, Italy, Greece, Turkey, Peru and Haiti). However, building typologies like Pombalino buildings in Lisbon have not experienced seismic activity and therefore their behaviour is unknown. Pombalino buildings and others are under risk of failure during seismic events if their mechanical behaviour is not properly quantified and understood. Traditional timber framed walls exhibit nonlinear hysteretic response under in-plane cyclic loading. It is important to define numerical modelling strategies for this type of constructive element in order to understand their mechanical behaviour.

Timber frame walls create an internal timber skeleton that can reduce the out-of-plane vulnerability of solely masonry constructed walls. Due to their low cost these types of walls exist in several countries especially in the local vernacular architecture. They can be composed of various infill materials ranging from brick and stone masonry to mud and cane. The timber not only better resists horizontal loads, but also provides a confining effect on the masonry structure improving its mechanical properties [1].

Timber shear wall systems are typically composed of internal braces forming an X-shape called the Cross of St. Andrew and are typically found in seismic countries such as in Italy and Portugal. Portuguese Pombalino buildings, introduced after the 1755 earthquake and subsequent tsunami and fire by the prime minister of the time, the Marquis of Pombal, consist of external load bearing masonry walls and internal timber-framed shear walls (Figure 1), called frontal walls [2]. In Italy, the so called “casa baraccata”, introduced after the 1823 earthquake by the Borbone house, has a timber frame also embedded in the exterior masonry walls [3]. In Greece and Turkey a variety of timber-framed structures can be found (Tsakanika and Mousakis 2010; Guney 2006) and they have proved to resist well to seismic actions when appropriately maintained. Of course these constructions also represent typical vernacular architecture for non-seismic regions, such as Germany, France, the UK, and in general all northern European countries.

Figure 1: Frontal walls in Pombalino building

The different connection types and geometry greatly affects the dissipative capacity of the walls. It is specifically because of these differences that researchers have started studying in detail the behaviour of traditional timber frame constructions.

Few works are available in literature on the numerical modelling of traditional timber-framed structures, while more literature is available on modern timber frames. Portuguese Pombalino walls were modelled using non-linear properties in a 2-D model and adding a hysteretic model for the joints [4] [5]. Quinn and D'Ayala [6] modelled Peruvian timber frames adopting semi-rigid spring elements calibrated on experimental results.

Opensees is an open source software which allows to use and alter existing hysteretic models. It has great potential for timber modelling and various works can be found on such field

This paper presents a procedure for the development of a working timber frame model subject to in-plane cyclic loading.

2 SUMMARY OF EXPERIMENTAL RESULTS

To study the seismic response of traditional Portuguese timber frame walls, quasi-static in-plane cyclic tests were performed on real scale specimens [1]. Half lap joints were used for the connections between the elements of the main frame, while the diagonals were simply nailed to the frame. In general the walls showed a good capacity and ductility. Results greatly varied depending on the level of vertical pre-compression and on the presence of infill, which could alter the response of the wall from a shear one to a flexural one [1].

From the previous experimental campaigns [1] [7], the following observations can be deduced:

1. Nonlinear behaviour of the bottom connections influences the overall response of the walls leading to a predominant rocking (flexural) mechanism. The observed strength degradation and pinching in the wall response is related to the observed pinching behaviour of the tested connections due to immediate loss of strength;
2. Infill walls tested at lower vertical load levels resulted in generally smaller opening of connections because walls rotated as a whole limiting local deformations in connections, however, at higher load levels deformations were larger;
3. Timber frame walls experienced larger deformations and damages at the joints under both vertical load levels since absence of infill material created a prevalent shear resisting mechanism allowing for unrestricted deformations;
4. Deformation of frame members while applying load was generally caused by uplifting of the posts from the bottom beam leading to elongations of the diagonals inducing high shear concentration within the central connection and resulting in failure. Movement of diagonals is larger in unfilled timber frame walls;
5. Unloading of the walls is influenced by the difficulty of the post to recover its original position due to the plastic deformation of the nail;
6. The quality of interlocking in the connections increases the loading capacity of the nail connector. Out-of-plane opening occurs due to asymmetry in thickness of half-lap connections;
7. Bottom beam did not uplift from steel profile for all tests conducted on walls and frames.

For a full description of the experimental results, see Poletti and Vasconcelos [1].

The identified locations of nonlinearities within the frame, namely the joints, were used in the development of a working numerical model. Nonlinear response of the tested traditional connection helped in the calibration of uniaxial material models available in OpenSees.

3 NUMERICAL MODELLING OF EXPERIMENTAL RESULTS

The geometry of the model is representative of the timber frame tested at the Laboratory of Structures at the University of Minho. A simplification to the member length was made to create a square frame consisting of four equal cells having the dimensions 0.95 x 0.95 m2 for a total height and length of 1.90 m. All members have the same cross sectional areas except for the top and bottom beams. The modulus of elasticity for the timber elements is 1.1 x 107 kN/m2 according to experimental testing on the wood species *Pinus pinaster*.

Horizontal and vertical timber members of the timber frame wall (Figure 2 right) are modelled as nonlinear beam-column elements to allow for nonlinear analysis. The diagonal bracing members are modelled as truss elements transferring only tensile and compressive forces. The member sections are modelled as elastic without shear deformations. Appropriate linear co-ordinate transformations were applied to transfer local coordinates of the members to global coordinates of the frame model. The base nodes remained fixed while the global response is controlled by the calibrated springs.

All end nodes of members in the frame were duplicated at joints for the insertion of two-node link elements as springs in order to assign uniaxial material models applied in corresponding direction of influence. The central connection was separated into 8 pairs of two-node links. For the 2-D model, three degrees-of-freedom are considered for the links, namely translations along x (direction 1), translations along y (direction 2), and rotations about local z-axis (direction 3). This element has zero length and couples the rotations and translations of connected nodes sharing the same global coordinates (Figure 2 right).

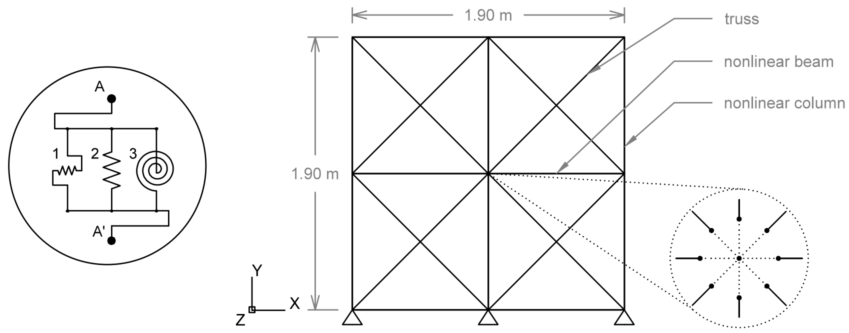

Figure 2: Schematic of the numerical model: two-node link element (left) and frame geometry (centre).

The response of the tested half-lap connection was first analysed (Table 1 and Figure 3) in order to calibrate two-node link elements acting as springs with the appropriate uniaxial material model to represent the global hysteretic behaviour in three directions: axial, shear, and rotations. Two-node link elements are applied at the base supports and in all internal elements while the outer frame was assumed to remain elastic. Calibrated uniaxial material models were used in the definition of the base supports and in appropriate connections within the timber frame.

Table 1: SAWS parameters for calibration of rotational spring.

Parameter	25 kN	50 kN
Intercept strength of shear wall spring element, F0	5.5	7
Intercept strength for spring element pinching branch, FI	0.65	1
Spring element displacement at ult. strength, DU	0.015	0.015
Initial stiffness of shear wall spring element, S0	473	500
Stiffness ratio of the asymptotic line, R1	0.12	0.12

Stiffness ratio of the descending branch, R2	-0.065	-0.09
Stiffness ratio of the unloading branch, R3	2	6
Stiffness ratio of the pinching branch, R4	0.055	0.055
Stiffness degradation parameter for the shear wall spring element, alpha	1.35	1.7
Stiffness degradation parameter for the spring element, beta	1.2	1.2

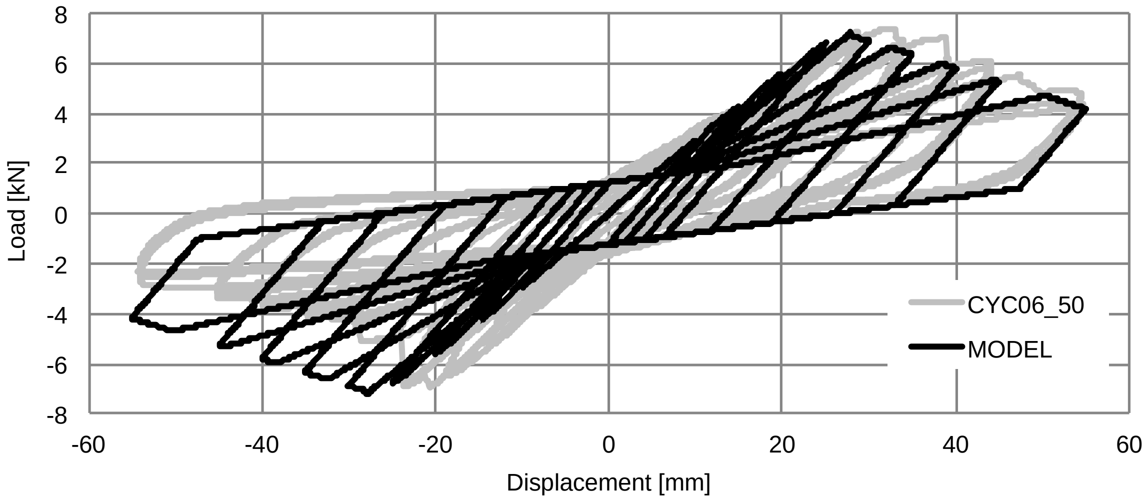

Figure 3: Calibration of rotational spring with SAWS for single joint

Three timber frame models (Figure 4) were studied with different configurations of springs in an attempt to achieve the experimental results, mainly the nonlinear (hysteresis) loops in the global load-deformation curve and the uplift of the base connections.

All diagonal members have Pinching4 in the axial direction with either elastic no-tension (ENT) and elastic-perfectly plastic gap (PP gap), element in parallel in order to make sure they work only in compression and are not depicted in the schematics for simplicity. In order to replicate the shear damage observed in the central connection, SAWS was added in the axial direction within the definition of the horizontal beam two-node link for Models 1 and 2.

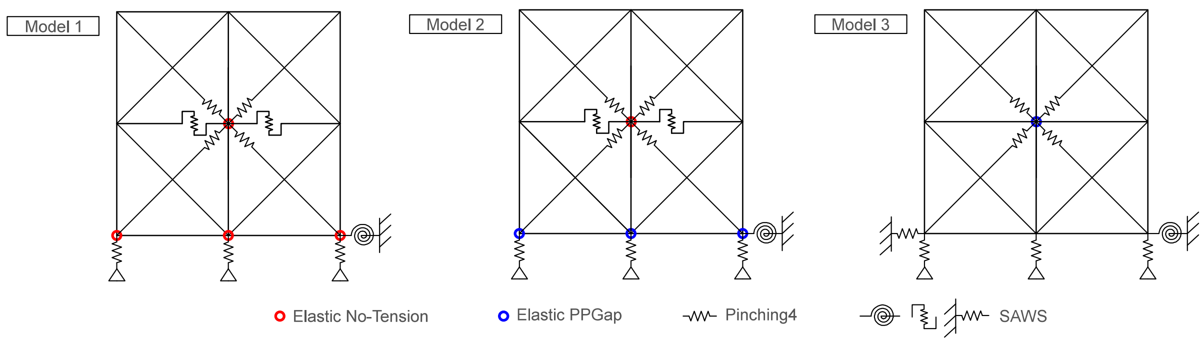

Figure 4: Studied models for timber frame wall with varying locations of nonlinearity

Timber frame model 1 was constructed with Pinching4 in the axial direction and SAWS in the rotational direction at the base while the shear response remained elastic to induce flexural (rocking) behaviour. Due to issues with convergence and to better represent the nail pull-out an ENT material with large stiffness was used in parallel with Pinching4. This configuration is also used in the axial direction for all diagonal members.

Timber frame model 2 is similar to model 1 except that the base connections have a compression-only PP gap element with a large strength in parallel with Pinching4. A gap of 2 mm was defined as measured in the pull-out of the nail connectors. This element was used to induce the flexural rocking mechanism (one post uplifts while the opposite crushes).

Timber frame model 3 was constructed with Pinching4 in the axial direction and SAWS in the rotational direction at the base. Nonlinearity in shear was added using the calibrated SAWS model with a larger intercept strength and initial stiffness of the spring. Pinching4 was also used in the axial direction for diagonals joining at the central connection. No gap element was used in parallel with Pinching4 in the base connections, instead a larger compression backbone was defined to avoid crushing of the bottom beam.

The pushover analysis was conducted using increments of 0.1 mm for a maximum displacement of 90 mm. The cyclic analysis used the same increment spacing with the following displacement cycle-peaks: 15 mm, 30 mm, 40 mm, 50 mm, 60 mm, and 70 mm. The cyclic analysis was performed only up to 70 mm due to early failure of UTW50 at 70.85 mm [1].

4 ANALYSIS AND DISCUSSION OF RESULTS

After initial analysis attempts of timber frame model 1, it was clear that the proposed configuration does not result in a comparable load-deformation response (Figure 5a). The initial stiffness and overall load capacity of this model is not representative of the experimental results. However, the model, in general, is able to reproduce damage (shearing) of the middle beam at the central connection and sliding of diagonal members which is in accordance with damages achieved in the experimental testing.

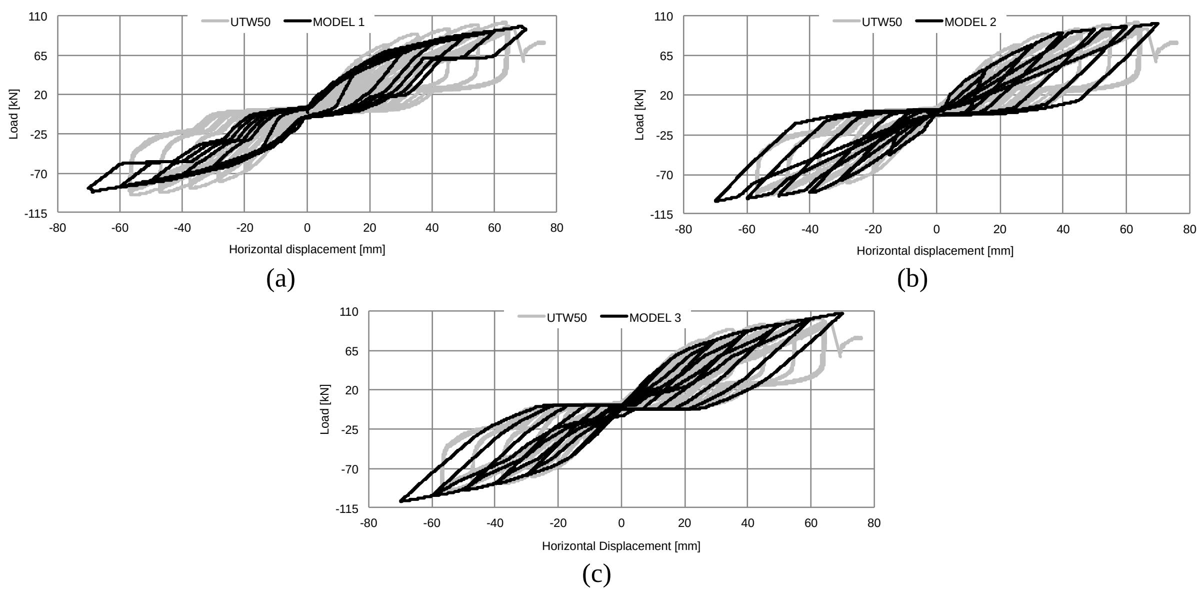

Figure 5: Comparison between experimental results and model output: (a) model 1; (b) model 2; (c) model 3.

The initial stiffness and overall load capacity of timber frame model 2 and timber frame model 3 is representative of the experimental results. However, in timber frame model 3 the hysteresis loops are poorly defined and reloading is minimal (Figure 5c). Timber frame model 3 does not replicate sliding of the diagonals or damage in the central connection. The resisting mechanism is shear at the base as evident by the global lateral movement of the frame. It is considered that this deformed shape is not acceptable when compared to experimental results given that no sliding at the base was recorded during the experiment.

Timber frame model 2 best represents the global response of the experimental results. Concentrating the nonlinearities at the base and in the central connection proved to be reasonably accurate. Elastic PP gap elements in the axial direction in parallel with Pinching4 at the base induce the nonlinear (hysteresis) response while SAWS controls the rocking behaviour. Pinching4 in parallel with elastic no-tension results in the diagonals acting in compression only. Visible damage of the central connection and sliding of the diagonals is not noticeable, possibly due to the gap material at the base that restricts movement of the diagonals and prevents shearing of the middle beam.

Timber frame model 2 was selected and updated to include the confining and stiffening effect of masonry in a simplified way by deleting nonlinearities in the central connection and only controlling behaviour at the base, based on the experimental results observed, since infill would induce a rocking response in the wall. Stiffness of the diagonal members and the connections was increased to 1.65 x 107 kN/m2. The backbone of the tension side of Pinching4 was also increased to better capture the total load capacity and initial stiffness. SAWS in the base connections was adjusted to include the large intercept strength of the spring for the pinching branch. The model is comparable to the results of UIW50 experimental testing up to the first failure of the specimen occurring at 70 mm horizontal displacement [1].

4.2 Influence of aspect ratio

A study was conducted on the developed half-timbered frame model considering different geometric configurations. The influence of the height to length ratio on the lateral response of the wall is compared with initial stiffness and load capacity. Also compared is the lateral load-drift response and cumulative energy dissipation between wall configurations.

The geometric configurations for both wall types are analysed and compared using a total drift of 10% with displacement cycle-peaks at 1% increments of total height (Table 2).

Table 2 Initial stiffness and load capacity for different configurations of half-timbered walls

Wall	Aspect ratio [H/L]	Maximum Load [kN]	Initial Stiffness, K_{in} [kN/mm]
1x2	0.5	340.25	53.13
2x2	1	170.12	18.54
3x2	1.5	113.41	8.41
1x1	1	105.56	16.00
2x1	2	52.78	4.19
3x1	3	35.18	1.70

Results from the parametric analysis show that the response of the timber-framed walls with infill (half-timbered walls) is similar to the response of timber frame walls except with an increase of initial stiffness (Figure 6a). The loading capacity remained the same since the influence of masonry was defined in the model by only changing modulus of elasticity in the diagonal members and connections. A similar exponential trend for load capacity and initial stiffness with increasing height to length ratio was observed (Figure 6b).

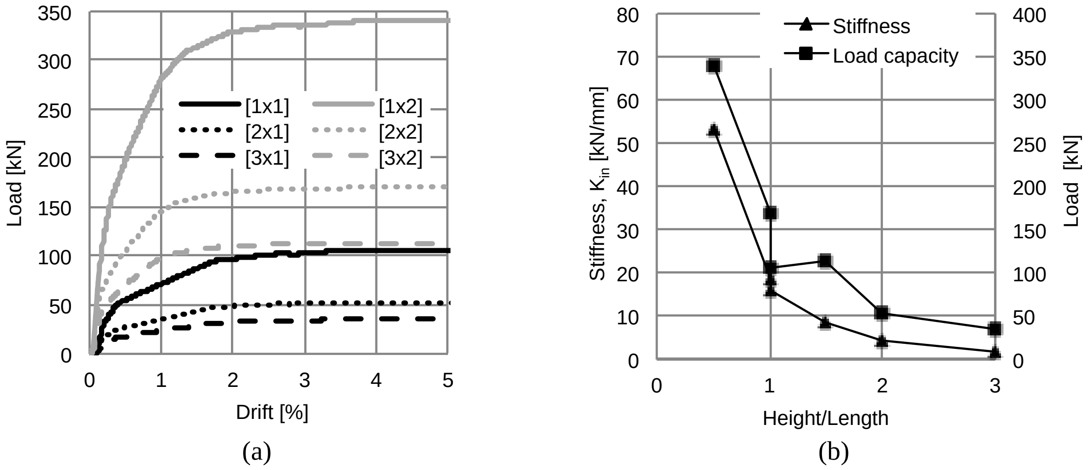

Figure 6: (a) Influence of the height to length ratio on the lateral response of half-timbered walls; (b) initial stiffness and load capacity

5 CONCLUSIONS

- Timber-framed infill walls have a complex behaviour resulting from material properties, interfaces, connection detailing, and quality of workmanship.
- Simple models are necessary to reduce the computational effort and obtain user-friendly models.
- Opensees was usefull in providing existing hysteretic models that could be calibrated on existing experimental results, with the disadvantage of a large number of parameters to be calibrated.
- Height-to-length ratio greatly influences strength, stiffness and energy dissipation.
- A macro-model will be developed based on these results in order to further simplify the model and develop of a set of rules for analysing timber-framed structures under horizontal loadings where hysteretic behaviour, pinching, stiffness and strength degradation as well as locations of energy dissipation and damage are characterised.

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